Infinite spin diffusion length of any spin polarization along direction perpendicular to effective magnetic field from Dresselhaus and Rashba spin-orbit couplings with identical strengths in (001) GaAs quantum wells

K. Shen and M. W. Wu*

Hefei National Laboratory for Physical Sciences at Microscale and Department of Physics, University of Science and Technology of China, Hefei, Anhui, 230026, China

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In this note, we show that the latest spin grating measurement of spin helix by Koralek *et al.* [Nature **458**, 610 (2009)] provides strong evidence of the infinite spin diffusion length of any spin polarization along the direction perpendicular to the effective magnetic field from the Dresselhaus and Rashba spin-orbit couplings with identical strengths in (001) GaAs quantum wells, predicted by Cheng *et al.* [Phys. Rev. B **75**, 205328 (2007)].

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As one of the spintronic focuses, manipulations of electron spin in spin-orbit-coupled solid state systems have been extensively investigated due to the potential application in future quantum computation and quantum information processing.[1] In confined semiconductors with zinc-blende structure, both the Dresselhaus spin-orbit coupling (SOC)[2] due to the bulk inversion asymmetry and the Rashba one[3] due to the structure inversion asymmetry are present, and the interplay of them gives rise to amazing effects as reported in the literature.[4,5,6,7,8,9,10,11,12,13] For example, an infinite spin relaxation time for spin-polarization along the (110) [or ($\bar{1}$10) depending on the sign of the Rashba term] direction was predicted by Averkiev and Golub[4] in (001) GaAs quantum wells (QWs) when the cubic term of the Dresselhaus SOC is excluded, and the two leading terms, i.e., the linear Dresselhaus term and the Rashba one, are of the same strengths. With the cubic term, the spin relaxation time along the (110) direction becomes finite, but still much longer than those in the other directions.[6] Bernevig *et al.*[8] predicted a persistent spin helix (PSH) by analyzing the symmetry with identical Dresselhaus and Rashba strengths, which was observed by Koralek *et al.*[11] in the latest transient spin grating experiment.[14] Moreover, Cheng *et al.*[12] studied the anisotropic spin diffusion/transport in (001) GaAs QWs with identical Dresselhaus and Rashba strengths and predicted that in the direction perpendicular to the effective magnetic field from the Dresselhaus and Rashba terms, i.e., ($\bar{1}$10) if the later is along the (110) direction,[15] the spin diffusion length is infinite *regardless of* the spin polarization direction. It seems rather strange that the spin diffusion length can be still infinite for the spin polarization direction other than the direction of the effective magnetic field. According to the well-known relation $L_s = \sqrt{D_s\tau_s}$ widely used in the transient spin grating works,[16] only a finite spin diffusion length L_s can be obtained for a spin polarization other than the (110) direction, because the spin diffusion coefficient D_s and the spin relaxation time due to the D'yakonov-Perel' (DP) mechanism[17] τ_s are both finite. However, to determine the spin diffusion length via the transient spin grating signal, as pointed out by Weng *et al.*,[13] the correct expression should be

$$L_s = \sqrt[4]{D_s^2\tau_{s1}\tau_s}/\sin\tfrac{\phi}{2}. \tag{1}$$

This formula naturally gives an infinite spin diffusion length because $\phi = 0$ for identical Dresselhaus and Rashba strengths.[13] In the following part, we will discuss the underlying physics of the ideal spin injection along the ($\bar{1}$10) direction and show that the corresponding injection mode is the same as the PSH mode[8] in the transient spin grating along the ($\bar{1}$10) direction.[15] Therefore, the observation of the PSH also gives strong evidence of the ideal spin injection/diffusion efficiency along the ($\bar{1}$10) direction predicted by Cheng *et al.*.[11] Similar to the spin relaxation time along the (110) direction, the small cubic term of the Dresselhaus SOC makes the spin diffusion length along the ($\bar{1}$10) direction finite, but still much longer than those along other directions.

The origin of the infinite spin diffusion length in the steady-state spin injection along the ($\bar{1}$10) direction in (001) QWs was explained by Cheng *et al.*, associated with the inhomogeneous broadening.[12] For spin transport along the x-axis, the inhomogeneous broadening is determined by the procession frequency $\boldsymbol{\omega}_{\mathbf{k}} = \frac{m}{2\hbar^2 k_x}\boldsymbol{\Omega}(\mathbf{k})$,[12,13,18,19] with $\boldsymbol{\Omega}(\mathbf{k})$ and m representing the effective magnetic field from the Dresselhaus and/or Rashba terms with momentum $\mathbf{k}$ and the effective electron mass, respectively. When the Rashba coefficient α equals to the linear Dresselhaus coefficient β, $\boldsymbol{\omega}_{\mathbf{k}}$ reads[12]

$$\begin{aligned}\boldsymbol{\omega}_{\mathbf{k}} \;=\; & \frac{m}{2\hbar^2}\Bigg\{2\beta\left[\sin\left(\theta-\frac{\pi}{4}\right)+\cos\left(\theta-\frac{\pi}{4}\right)\frac{k_y}{k_x}\right]\hat{\mathbf{n}}_0 \\ & +\gamma\left(\frac{k_x^2-k_y^2}{2}\sin 2\theta + k_xk_y\cos 2\theta\right)\begin{pmatrix}\frac{k_y}{k_x}\\ -1\\ 0\end{pmatrix}\Bigg\},\end{aligned}$$

with $\hat{\mathbf{n}}_0$ denoting the crystal direction (110). θ stands for the angle between the injection direction x and the

(100) crystal axis. The second term with coefficient γ on the right side of the equation is the cubic Dresselhaus term, which we neglect in the following discussion for simplification. For spin injection along the $(\bar{1}10)$ direction, i.e., $\theta = 3\pi/4$, the precession frequency becomes $\boldsymbol{\omega}_{\mathbf{k}} = \frac{m\beta}{\hbar^2}\hat{\mathbf{n}}_0$, which is independent of the momentum $\mathbf{k}$. Therefore there is no inhomogeneous broadening in this case.[12] As a result, the spin polarization diffuses into the semiconductor without any decay of the amplitude for the steady-state spin injection condition, even with all the relevant spin-conserving scatterings, such as, the electron-impurity, electron-phonon and electron-electron scatterings. Moreover, the spin-1/2 electron ensemble with a unique precession frequency $\boldsymbol{\omega}$ gives the spatial spin oscillation period $L_0 = 2\pi/(2m\beta)$, along the diffusion length.[12]

The infinite spin diffusion length was also associated with the transient spin grating by Weng *et al.*.[13] In the transient spin grating along the $(\bar{1}10)$ direction, the initial spin-orientation wave is composed of two spin helices, which decay with different rates.[8,9,11,13] For $\alpha = \beta$, the slow-decay helix exactly matches the spin precession mode when the wave vector q equals to $2m\beta$ (the corresponding spatial period $L_0 = 2\pi/(2m\beta)$).[20] Therefore, this mode becomes PSH with the relaxation time $\tau_- = \infty$ and dominates the steady-state spin injection,[13] while the other one decays with finite τ_+ as usual.[8] By directly integrating the transient spin grating signal over the time from 0 to ∞ and the wave vector q from $-\infty$ to ∞, the steady-state spin injection solution is $S_z(x) = S_z(0)e^{-x/L_s}\cos(x/L_0 + \psi)$ with the spatial oscillation period $L_0 = \sqrt[4]{D_s^2\tau_{s1}\tau_s}/\cos\frac{\phi}{2}$ and the spin diffusion length L_s [shown in Eq. (1)].[13] Since $\tau_{1s} = \tau_s$ and $\phi = 0$ for $\alpha = \beta$,[13] one obtains $L_0 = 2\pi/(2m\beta)$ and $L_s = \infty$, which are coincident with those predicted by Cheng *et al.*.[12] Thus, the observation of the PSH strongly supports the prediction of the infinite spin diffusion length by Cheng *et al.*.[12]

In real systems, both the spin diffusion length in the steady-state spin injection and the spin lifetime of the PSH mode in the transient spin grating are finite because of the cubic Dresselhaus term. With this term, the optimal condition is $\alpha = \beta - \gamma k^2/4$ instead of $\alpha = \beta$,[11] as predicted theoretically.[7,12]. However, the direct quantitative measurement of the largest spin diffusion length still requires further experimental efforts.[21]

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* Author to whom correspondence should be addressed; Electronic address: mwwu@ustc.edu.cn.

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